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CONTINUED STUDIES OF PROGRAMMED-SPLITTING STICK PROPELLANT

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OCTOBER 1987

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ABERDEEN PROVING GROUND, MARYLAND

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A number of high-progressivity, high-density (HPD) propelling charge concepts are being investigated to provide significant improvement in muzzle velocity with minimal system impact. The particular approach presented in this paper is based on a concept which allows the charge designer to program a substantial increase in the burning surface at any desired time in the interior ballistic cycle, typically after peak pressure has occurred and the pressure is falling rapidly as the projectile moves downbore. Thus, a very high loading density charge can be employed without excessive burning surface leading to overpressurization early in the cycle or insufficient burning surface leading to incomplete consumption of the charge upon projectile exit. This concept, applicable to a number of propellant configurations, has been exploited first as programmed-splitting stick (PSS) propellant. Progress at the time of this writing is reported, including performance predictions, manufacturing experience, gun firings, and modeling efforts.

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I. INTRODUCTION

The objective of the High Progressivity/Density (HPD) Propelling Charge Concepts Program is to investigate the feasibility of safely obtaining significant increases in velocity, for a given maximum pressure, over conventional systems now being used. Moreover, this performance increase is to be obtained using existing propellant formulations and without invoking ballistic concepts such as traveling charge or light gas guns.

The velocity achieved by a particular projectile as it exits the muzzle of a gun is principally the result of the pressure history acting on its base while it travels down the bore of the tube. The maximum pressure value allowable is usually dictated by gun tube design, but the actual pressure profile, apart from this maximum value, exerted on the projectile base is a result of the competition between the quantity of gas produced by the burning propellant and the amount of free volume available. At the beginning of the event, the projectile is not moving or is moving only very slowly, so the pressure rises rapidly as the propellant burns. However, as the projectile speeds up, it eventually creates additional volume much faster than gases are created to fill it. As a result, in virtually all cases, the pressure falls off much more rapidly than desired.

Past attempts to counter this problem have most often involved the use of propellant configurations exhibiting a continuous increase in burning surface as a function of distance burned (e.g., 7-, 19-, or even 37-perforated grains). Less conventional approaches have included consolidated propellant charges (i.e., one or more compacted aggregates of individual propellant grains), offering an increase in total available energy and the potential for an additional increase in burning surface during the ballistic event as the aggregate deconsolidates. However, programmability and reproducibility of the deconsolidation event have presented serious challenges to the charge designer.

Concepts being considered under the HPD Program are programmed-splitting, perforation-augmented burning, erosive-augmented burning, pressure-supported perforation-augmented burning, monolithic charges, programmed ignition with deterrents or inhibitors, multiple granulations, and multi-layered propellants.

The approach to be presented in this paper is based on a concept by which the increase in surface area can be programmed to commence at the most useful time in the burning process, rather than being operative as soon as the propellant is ignited. Thus, a very high loading density charge can be employed without excessive burning surface and overpressurization of the gun early in the ballistic cycle. Second, this increase in surface area is, conceptually at least, unlimited. Thus, despite a desirably low initial burning surface, the programmed increase in burning surface after peak pressure can assure total burning of the charge before the projectile exits the gun, meeting the second major requirement for the use of very high loading density charges. This concept, applicable to a number of propellant configurations, has been exploited first as programmed-splitting stick (PSS) propellant and progress at the time of this writing will be reported.

II. THEORETICAL

Many gun systems utilize 7-perforated granular propellant as the main propellant charge. If the same charge weight as used in the 7-perforated charge is assumed to burn such that the maximum velocity is obtained (a constant pressure calculation), a velocity increase of only about 5% over that of an optimized 7-perforated charge is predicted. Therefore, not only a near-optimum burning surface profile (i.e., extremely progressive) but also more total energy (i.e., greater charge weight) is required in order to achieve greater increases in velocity.

Particularly attractive in respect to both of these requirements is the programmed-splitting propellant concept, which effectively decouples the burning surface after peak pressure from that preceding it. This concept provides for a discontinuous increase in burning surface at any desired regression distance, at which point the burning surface reaches an embedded array of slits and the flame envelopes the additional surface area. A programmed-splitting stick (see Figure 1) was selected for initial study because it seemed to be manufacturable with current extrusion technology, to offer a very high loading density, and to provide the fault-tolerant, ignition benefits of a stick propellant configuration. The same concept can be applied to slab or scroll propellant configurations, but manufacturing problems were felt to be greater. Any of these configurations, of course, requires that the ends or edges where the slits are initially exposed be adequately inhibited to prevent the flame from prematurely reaching the slits. NOSOL 363 Propellant (Lot RAD-1-2-73) was chosen for this initial effort because it is extruded without solvents and potential problems with drying would be reduced; in addition, the sheet stock was readily available.

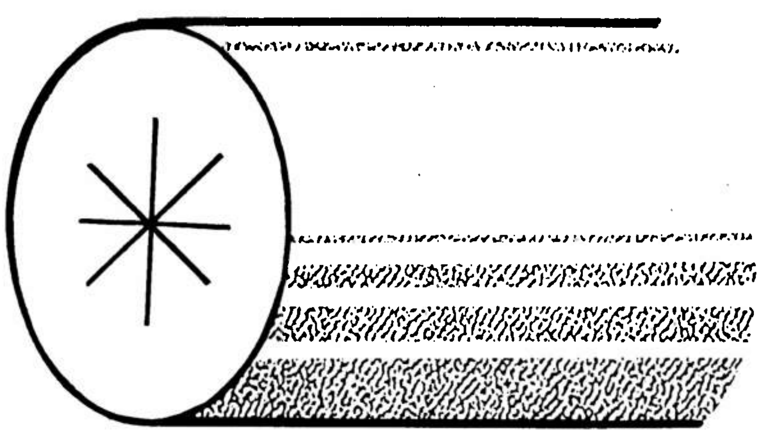

Figure 1. Programmed-Splitting Stick Propellant

The programmed-splitting stick propellant configuration was modeled as a cord until the slits were reached and then as long pie-shaped wedges. The slits were assumed initially to occupy no volume. The optimization process involved first determining the proper cord geometry to achieve the desired maximum pressure and then defining the slit parameters (numbers and dimension) to raise the pressure to this same value once again, as shown in Figure 2. Clearly, a multiplicity of such grain configurations could be employed to achieve an even greater number of peaks, approaching the optimal flat pressure-time curve. However, even the single, basic configuration with three or four slits of the same dimensions (yielding six or eight pie-shaped wedges) was calculated to provide a significant increase in performance for the 155-mm Howitzer.

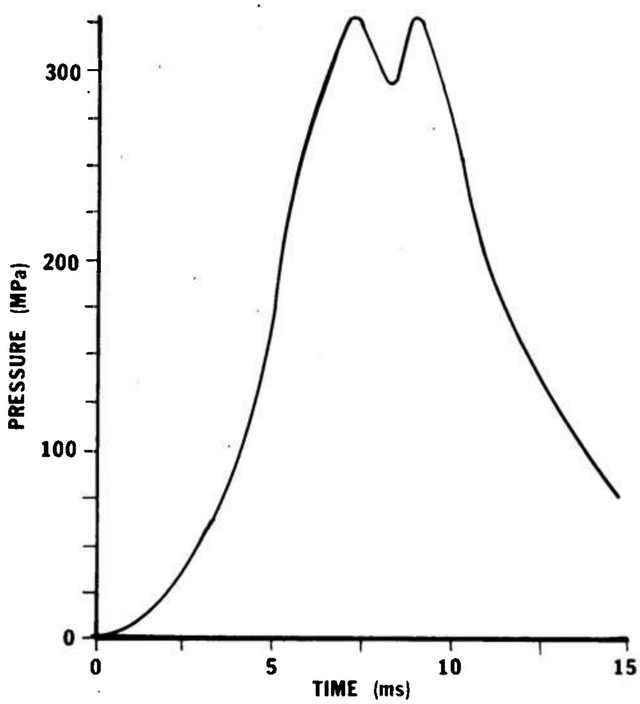

Figure 2. Calculated Pressure-Time Profile for Programmed-Splitting Stick Propellant

Loading experiments indicated that approximately 18.1 kg of a right circular cylinder of density of 1.54 g/cc (that of NOSOL 363 Propellant) could be loaded into the chamber of a 155-mm Howitzer with a M101 Projectile. To allow for manufacturing defects and for some ullage exterior to the sticks (to prevent overpressurization due to the sticks burning in too small of a constrained volume), a charge weight of 16.3 kg was chosen. Calculations for 16.3 kg of NOSOL 363 Propellant in an eight-pie (four-slit) configuration resulted in a stick with a length of 760 mm, a diameter of 8.53 mm, and a slit width of 6.65 mm. This optimized charge would yield a velocity of 936 m/s at 328 MPa, a 13.3% velocity increase over the 826 m/s from the M203 Charge.

III. MANUFACTURING EXPERIENCE

Figure 3 shows a drawing of a stake and die used for extrusion experiments and for manufacturing the PSS Propellant described in this paper. These stakes and dies were used to make propellant to study the effects of the length of the stake on final PSS Propellant properties, extrusion temperature effects, and the subsequent production of enough propellant to perform exploratory gun firings. The dies were manufactured from stainless steel and had an average cylinder diameter of 8.33 mm. The stakes were machined from one piece of brass and had an average slit diameter of 6.58 mm.

The baseline length of the stake was 38.1 mm. This length brought the end of the stake flush with the end of the die cylinder (the normal condition for extruding perforated propellant). For the NOSOL 363 PSS Propellant, this baseline configuration left an internal voidage of approximately 10%. In an attempt to eliminate this voidage, the stakes were cut back by 3.2 mm, 6.4 mm, and 12.7 mm in length and extrusions with NOSOL 363 sheet stock of 1 kg samples were performed in a 50.8 mm press. A series of closed bomb and blowout bomb experiments was performed on these PSS samples. The sample made with the shortest stake extruded as a solid cord with no evidence of a memory of any slits. The closed bomb as well as blowout bomb firings and analyses gave burning rates and surface profiles consistent with a solid cord. The sample made with the stake shortened 6.4 mm gave a stick with little or no internal voidage with a suggestion of a memory of the slits. The slits were not well enough defined to be able to measure a band (the distance from the outside of the stick to

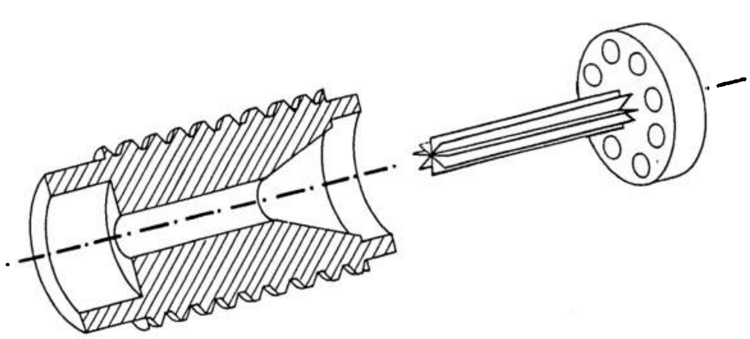

Figure 3. Die Design for Programmed-Splitting Stick Propellant

the tip of a slit). Closed bomb firings indicated a slivering of the sticks but not as large a surface area increase as desired. With this stick in the blowout bomb no slivering at all was observed to occur even though the burn distance was greater than twice that at which it was expected to sliver. [It was suggested that a thermal wave may have caused melting and a continuous self sealing.[1]] The stake shortened 3.2 mm gave two distinct samples, one which had near-zero internal voidage and well defined slits (Sample A) and one which had almost 5% voidage with well defined slits (Sample B). Sample A was believed to have been from the first ram of the extrusion press and its high density was believed to be a function of the initial extrusion conditions. Closed bomb firings on both Samples A and B indicated similar increases in progressivity. This increase in progressivity was similar to that seen in previous work.[2] In the blowout bomb, Sample A exhibited the self sealing as seen above but Sample B slivered and burned in the expected fashion.[1]

Extrusions of 1-kg samples were performed to test the effects of temperature on the resultant sticks. The temperature range from 55°C to 65°C produced no discernible differences in the dimensions of the sticks.

As a result of these processing studies, the decision was made to use stakes cut back 4.76 mm and an extrusion temperature of 60°C to make the pilot lots of PSS Propellant for exploratory gun firings. Approximately 100 kg of eight-pie (four-slit) PSS Propellant was extruded and designated Lot L1. The resultant sticks, cut to 750 mm, were not straight, probably because of the storage trays and packaging employed after extrusion and during transportation. The sticks had about 6% internal voidage. The sticks had an average diameter of 8.65 mm, an average slit width of 6.76 mm, and an average band width of 0.94 mm. The average minimum band width was 0.76 mm and the average maximum band width was 1.14 mm. Since there was voidage in the sticks the interior tips of the pies did not come together (see Figure 4). They were separated on the average by 0.64 mm. Due to the curvature of the sticks and the internal voidage, it was not possible to load a full, optimal-performance, 16.3-kg charge into the 155-mm Howitzer.

IV. GUN FIRINGS

The gun firings were performed at the Ballistic Research Laboratory's Sandy Point (R-18) Test Facility. These charges were fired in a 155-mm Howitzer with a M199 Cannon with six Kistler 607C2 pressure gages in the chamber: two in the spindle face, two at midchamber, and two at the initial position of the projectile base. Six pressure measurements were also taken at locations down the tube: 1.57 m, 2.63 m, 3.40 m, 4.16 m, 4.92 m, and 5.83 m from the rear face of the tube. The projectiles were inert M101's weighted to a mass of 43.1 kg. Velocity was measured with a 15 GHz continuous wave doppler radar as well as velocity coils nominally at 15 m, 22.5 m, and 30 m from the muzzle. M4A2 Charges were used as warmer rounds with M203 Charges used as checkout and control rounds.

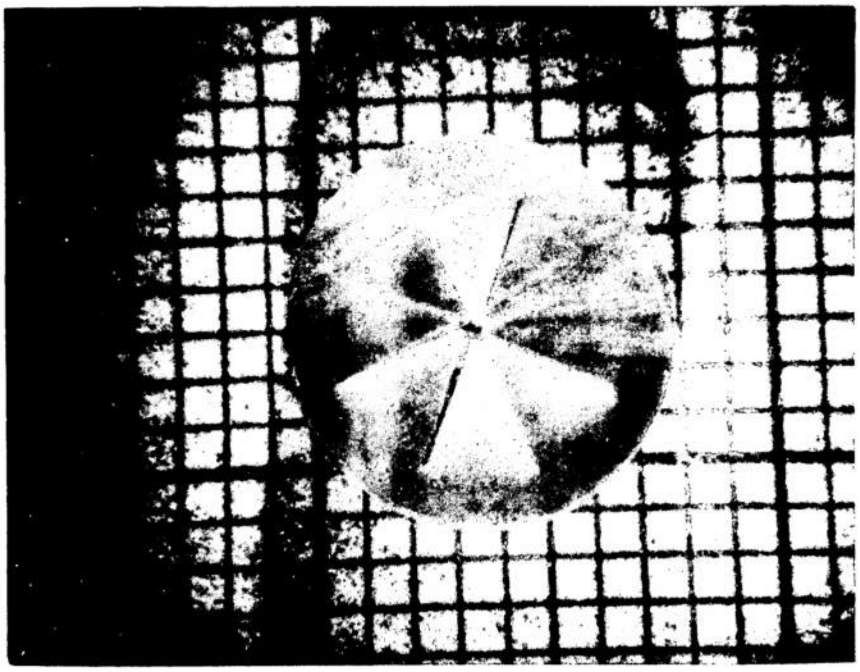

Figure 4. NOSOL 363 PSS Propellant Before Firing

End sealing of the PSS Propellant was accomplished by dipping each end twice in a solution of 50% acetone and 50% nitrocellulose-based glue (Stevens Industries adhesive and sealing compound, cellulose nitrate base, Type II, uncolored, Federal Specifications MMM-A-105), followed by dipping each end twice in 100% glue, with at least 24 hours between applications. The acetone/glue solution was allowed to penetrate the slits approximately 15 mm. A final application of spray paint was then applied. It is realized that this method of end sealing is cumbersome and labor intensive; however, the goal here was to end seal the propellant by whatever means was necessary to demonstrate a proof of the programmed-splitting stick concept.

The charges were assembled by weighing the propellant, end sealing the PSS Propellant, tying the sticks in cylindrical bundles with string and tape, and tying the igniter pad to the end of the charge. The igniter consisted of a basepad of 62 g of CBI with a 16-g spot of black powder, sewn in a cloth bag 125 mm in diameter. The NOSOL 363 PSS Propellant charge weights were: 8.17 kg, with no end sealing; 8.16 kg (8.22 kg with glue and string) with two dips; 10.0 kg (10.2 kg with glue and string) with four dips; 11.8 kg (12.0 kg with glue and string) with three dips (the last 100% glue dip was inadvertently not performed); and 13.6 kg (13.8 kg with glue and string) with four dips.

Figures 5-9 are the pressure-time curves measured at the spindle for each of the five PSS gun firings. Figures 10 and 11 are the midchamber and forward chamber pressure-time curves for the 13.6-kg gun firing. Table 1 gives a synopsis of the spindle pressures and velocities. Several observations can be made from the plots and tabular data. It is evident from the table that at least four dips are necessary for end sealing since the maximum pressure of the 11.8-kg charge is closer than would be expected to the maximum breech pressure of the 13.6-kg charge than to the 10.0-kg charge. However, it would appear that two dips have some end sealing effect since the 8.16-kg charge with two dips had a maximum breech pressure much lower than the 8.17-kg charge with no end sealing. Further evidence of the superiority of more than two end seal dips is demonstrated in the 60-m/s velocity increase, at the same maximum pressure, found in the 11.8-kg firing in comparision with the 8.16-kg firing. Lastly, it is noted for the 13.6-kg charge that the breech pressure shows the beginning of the formation of a second pressure hump. The midchamber and forward chamber pressure-time curves also show a broadening of the maximum pressure. There was no indication of any reverse pressure gradients being formed in any of the firings.

TABLE 1. 155-mm Howitzer Firing Data, NOSOL 363 PSS Lot L1

Charge Weight (kg)	End Seal (number of dips)	Number of Sticks	Maximum Breech Pressure (MPa)	Coil Velocity (m/s)	Doppler Velocity (m/s)
8.17	0	---	303	733	733
8.16	2	127	165	634	636
10.0	4	157	100	554	556
11.8	3	183	164	694	696
13.6	4	210	183	728	728

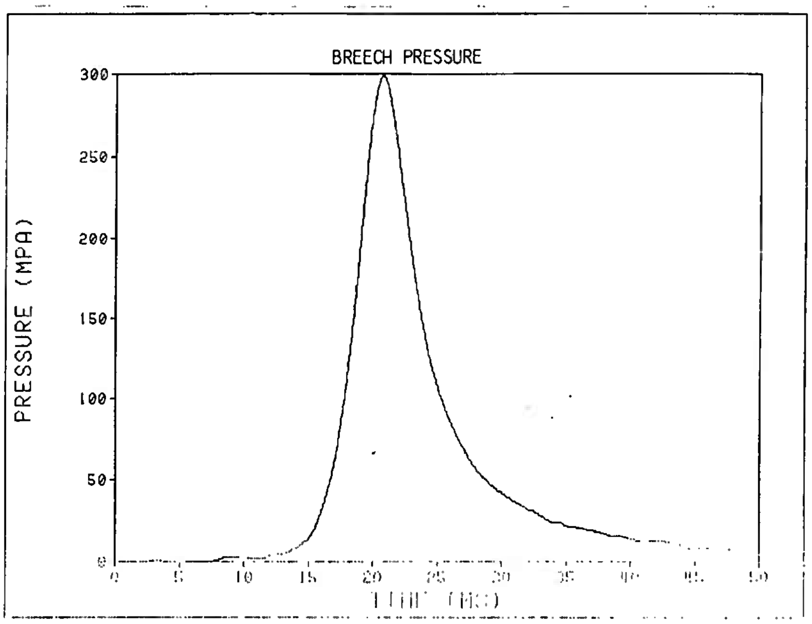

Figure 5. Breech Pressure, 8.17-kg PSS Charge, No End Seal Dips

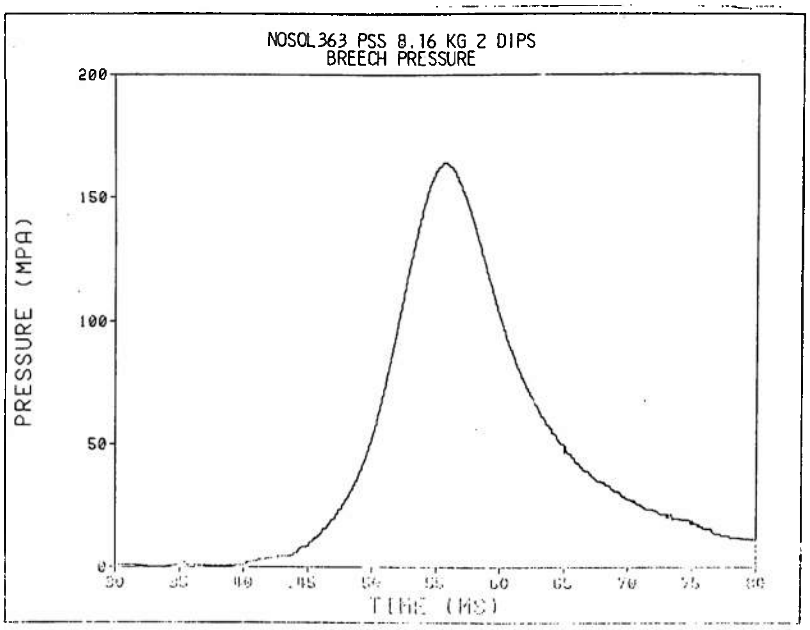

Figure 6. Breech Pressure, 8.16-kg PSS Charge, Two End Seal Dips

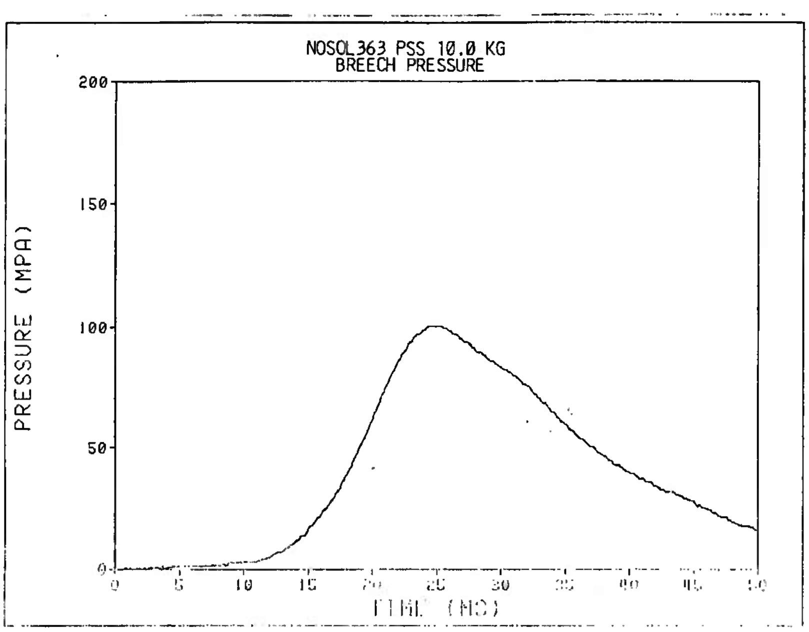

Figure 7. Breech Pressure, 10.0-kg PSS Charge, Four End Seal Dips

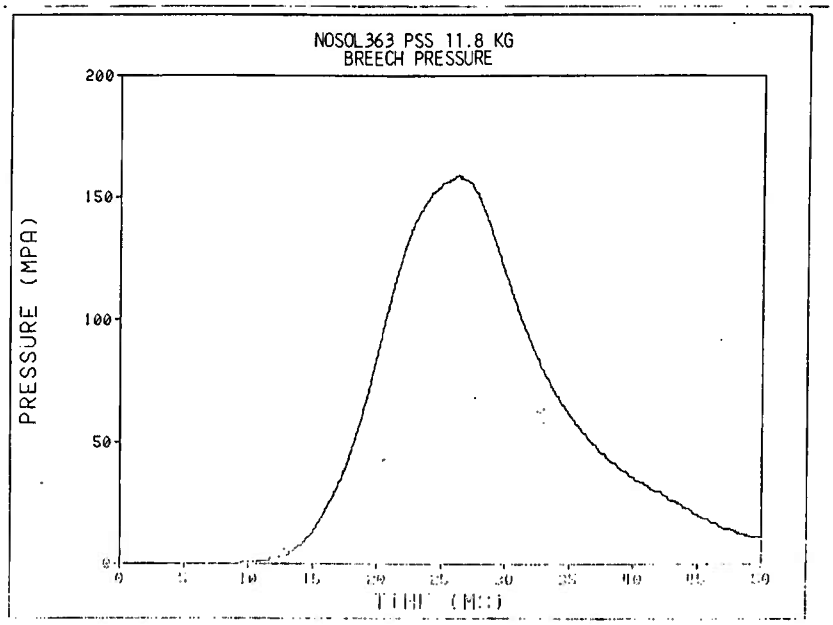

Figure 8. Breech Pressure, 11.8-kg PSS Charge, Three End Seal Dips

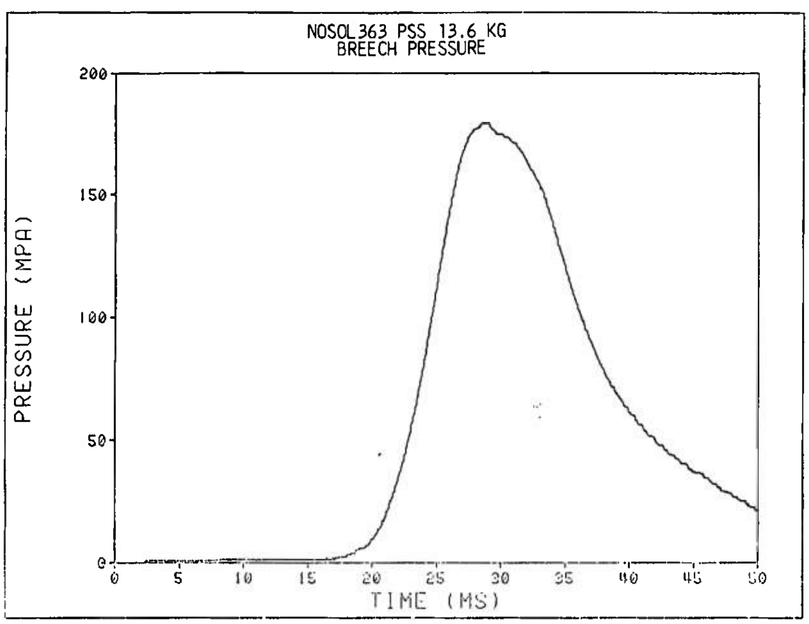

Figure 9. Breech Pressure, 13.6-kg PSS Charge, Four End Seal Dips

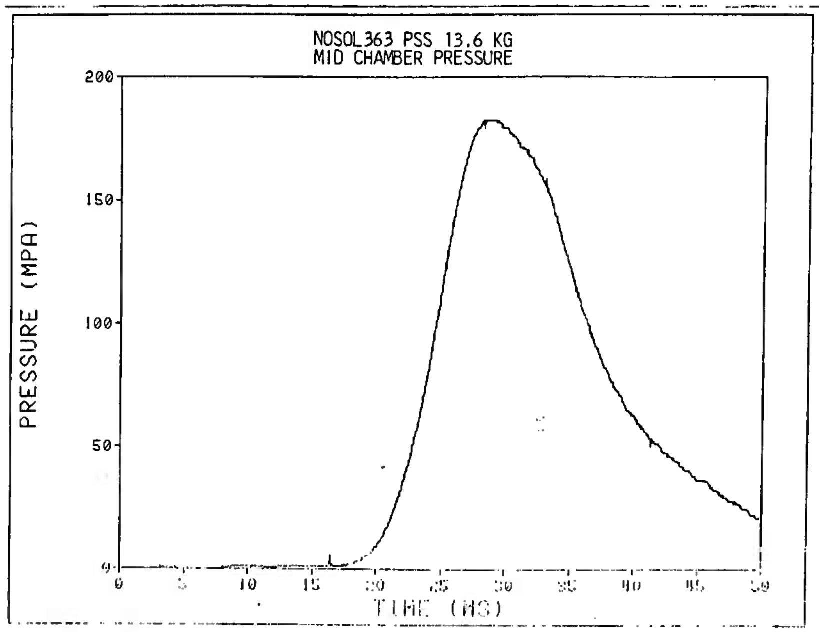

Figure 10. Midchamber Pressure, 13.6-kg PSS Charge, Four End Seal Dips

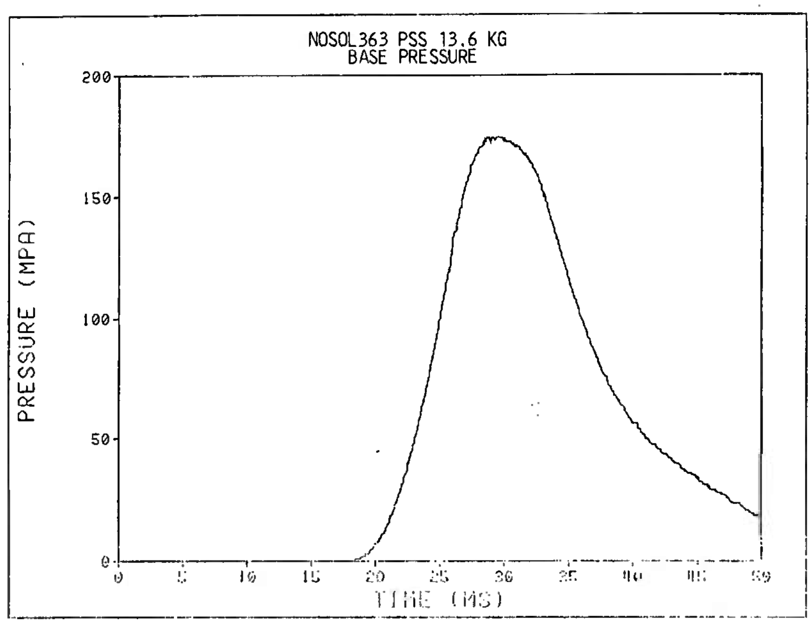

Figure 11. Forward Chamber Pressure, 13.6-kg PSS Charge, Four End Seal Dips

Since the charges fired were at less than the optimum charge weight, the pressures were correspondingly lower, and the expected unburned propellant was expelled from the gun and extinguished. Sections of the collected extinguished slivers from the 10.0-kg and 11.8-kg firings are shown in Figures 12-15. The appearance of the slivers is as would be expected if burning proceeded normal to the surface as is assumed in the modeled burning of the sticks. There are no rough surfaces at the edges of the periphery as may be expected if early stick collapse had occurred. For the 10.0-kg charge, the collected extinguished pieces had an average radial length of 1.80 mm with a minimum of 1.19 mm and a maximum of 2.29 mm. The average chord of the pie section was 1.47 mm with a minimum of 0.96 mm and a maximum of 2.18 mm. The average angle between the radii was 47 degrees with a minimum of 43 and a maximum of 53. The average length of the slivers was 100 mm. Figure 16 shows two end pieces collected indicating that some of the pie sections, but not all, remained glued together for 10-11 mm and that the end covering of pure glue had not burned through.

The corresponding measurements were performed on collected slivers from the 11.8-kg charge, but since the 11.8-kg charge was fired from the same gun immediately following the 10.0-kg charge, the collected sample probably contained some portion of slivers from the 10.0-kg firing. The average radial length was 1.57 mm with a minimum of 1.12 mm and a maximum of 2.08 mm. The average chord of the pie section was 1.07 mm with a minimum of 0.68 mm and a maximum of 1.78 mm. The average angle was 48 degrees with a minimum of 45 and a maximum of 56. The average length of the slivers was about 40 mm.

V. UPDATED CALCULATIONS

In order to be able to match the 13.6-kg gun firing it was necessary to make some assumptions regarding the PSS geometry and behavior. The sticks were assumed to be compressed from 8.65 mm outer diameter down to 8.41 mm outer diameter, reducing the internal voidage to near zero. Such a compression is easily done with finger pressure. The slot width was assumed to be 6.73 mm, defining a band width of 0.84 mm. It was also necessary to inhibit 67 mm of the 750 mm stick for 8 ms, or until about the time maximum pressure was reached, reflecting the behavior of the end sealed portion of the sticks. This model resulted in a calculated maximum breech pressure of 181 MPa and a muzzle velocity 730 m/s with a second pressure hump of 169 MPa about 5 ms after the first maximum pressure, a close match. This suggests that the four dips for end sealing are sufficient at this charge weight. With this model the calculated breech pressure for a 10.0-kg charge was obtained, but the calculated muzzle velocity was 491 m/s, much lower than experimentally seen. For the 11.8-kg charge a calculated maximum breech pressure of 137 MPa was obtained which is, as expected, lower than experimentally seen, suggesting that the fourth dip with pure glue is necessary to ensure a good end seal. The calculated velocity was 600 m/s. For all of these reduced-weight firings, the calculations predicted in-bore splitting and incomplete burning of the propellant, resulting in the expulsion of slivers from the gun tube.

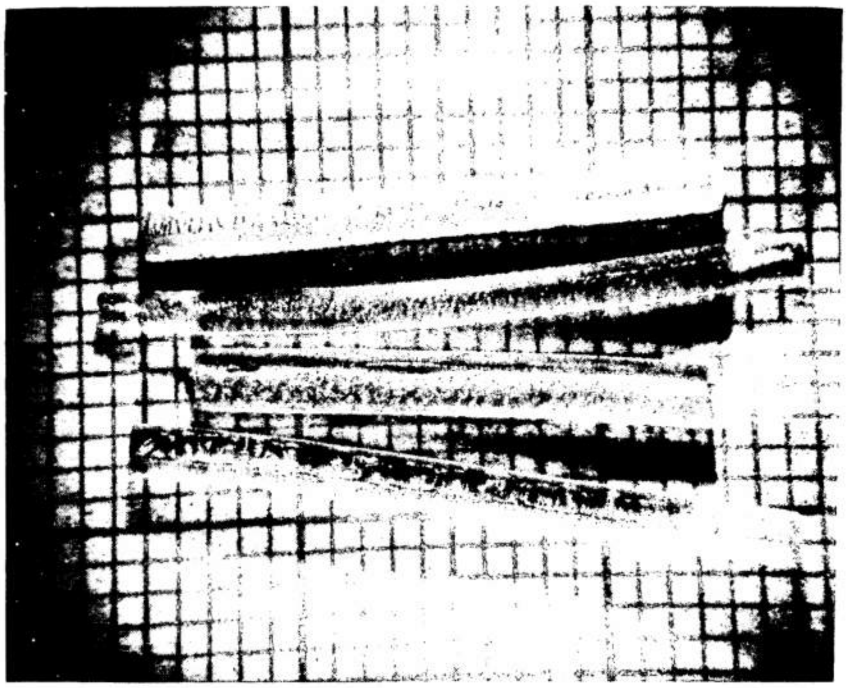

Figure 12. Extinguished NOSOL 363 PSS Propellant Samples Recovered After 10.0-kg Charge Firing (Longitudinal View)

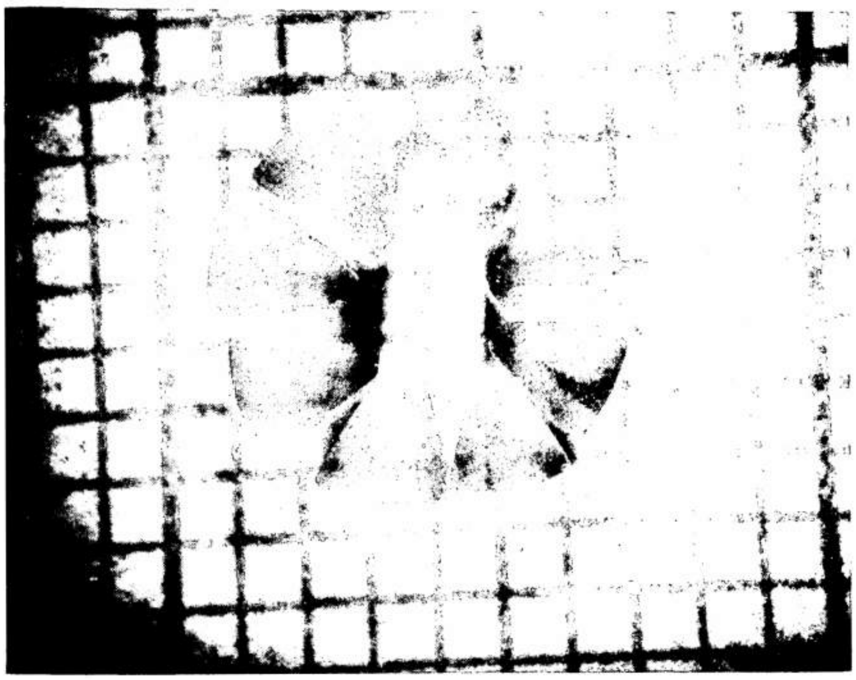

Figure 13. Extinguished NOSOL 363 PSS Propellant Samples Recovered After 10.0-kg Charge Firing (End View)

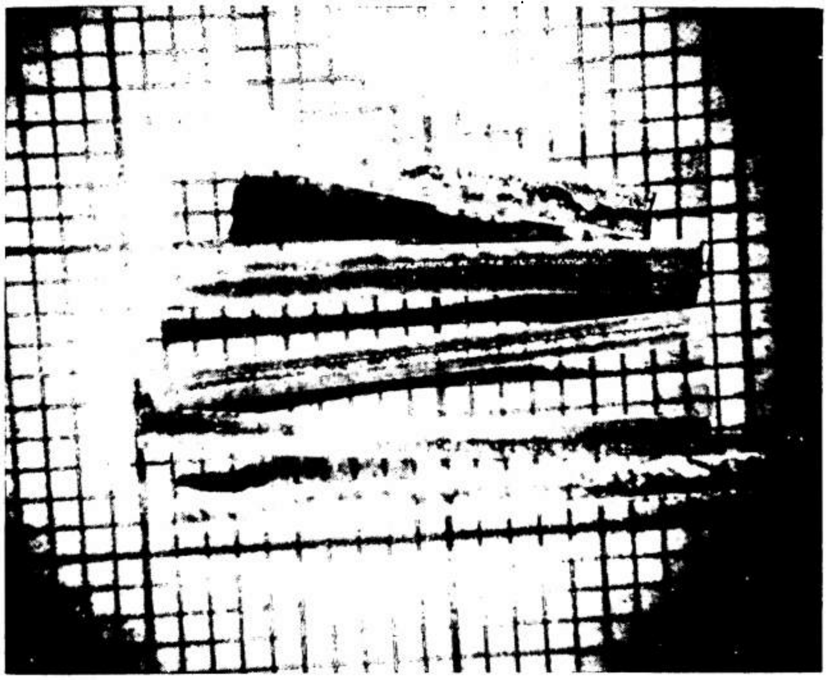

Figure 14. Extinguished NOSOL 363 PSS Propellant Samples Recovered After 11.8-kg Charge Firing (Longitudinal View)

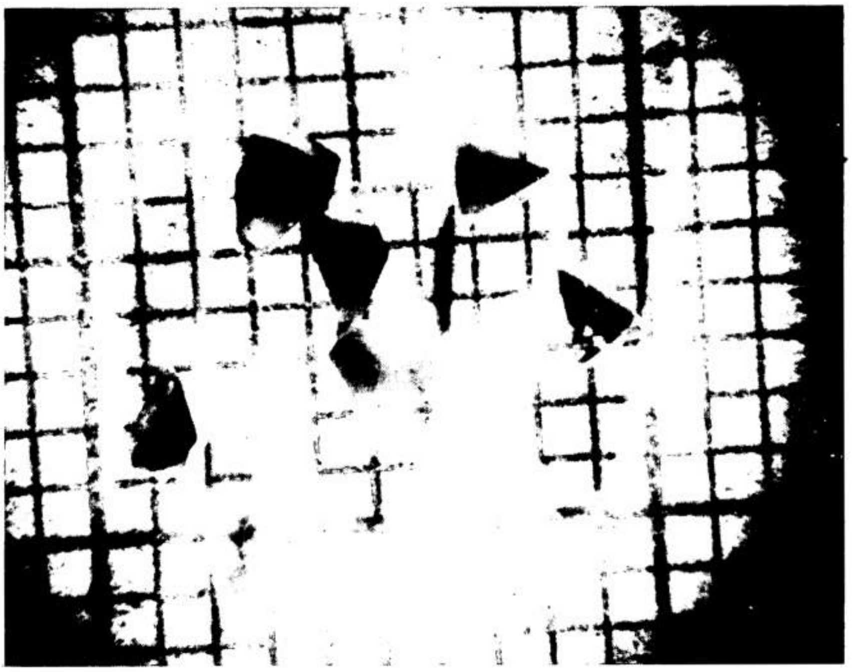

Figure 15. Extinguished NOSOL 363 PSS Propellant Samples Recovered After 11.8-kg Charge Firing (End View)

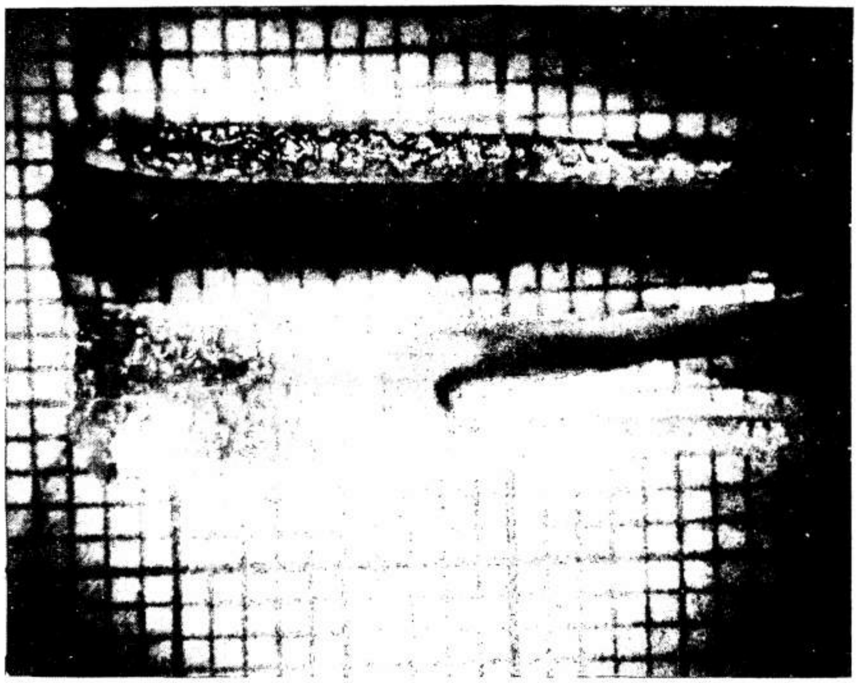

Figure 16. End Pieces of Extinguished NOSOL 363 PSS Propellant Recovered after 10.0-kg Charge Firing

Use of this model to calculate the performance of the desired 16.3-kg charge in the 155-mm Howitzer yields a velocity of 933 m/s at a maximum breech pressure for the second hump of 337 MPa, with the first pressure hump being 291 MPa. This velocity is a 12.8% increase over that of a standard M203 Charge, with little (2.7%) increase in maximum pressure. This calculation, based on gun firings and a physically reasonable model, agrees well with the initial performance estimate of a velocity of 936 m/s at a pressure of 328 MPa.

VI. CONCLUDING REMARKS

This report has presented the status of a particular concept being pursued under the BRL HPD Program - Programmed-Splitting Stick Propellant. This concept differs from those calling upon geometric progressivity developed in the past in that it relies on a sudden, programmed increase in burning area of the propellant, theoretically without limit, that translates into large increases in gun performance, well beyond the 2-3% increase in muzzle velocities associated with other geometrically progressive granulations such as 19- or 37-perforation propellant. The program has journeyed along well organized lines: concept development, model formulation and interior ballistic computations, propellant technology development, including methods of end sealing the propellant grains, diagnostic testing in the closed bomb and blowout fixtures, and finally, gun testing.

The work to date has demonstrated that programmed-splitting propellant remains a viable concept. Much of the propellant extrusion technology has been developed. Diagnostic testing has revealed the programmed increase in burning surface as required. Although the means employed for end sealing were far from ideal, techniques have been developed which permit ballistic testing. Limited gun tests have indicated that the concept works as envisioned, with calculated significant increases in velocity at a constrained pressure. An updated model, accounting for observed gun-firing data and employing physically reasonable assumptions regarding the grain behavior, still agrees well with initial predictions for the concept performance.

Though a ballistic demonstration of the programmed-splitting concept has been accomplished, there remain several areas of investigation which must be pursued before a final application of the concept can be made. Gun firings, while so far promising, have been extremely limited, and a larger data base will serve to improve our confidence in the concept. Although end sealing has been demonstrated to the extent necessary to indicate that the propellant concept holds promise, the methods employed to date have been cumbersome, and easier means and perhaps other sealants need to be found. Several parallel approches will be continued to arrive at this goal. The temperature sensitivity of programmed-splitting stick propellant will be thoroughly investigated, since historically, the more progressive a geometry, the greater the temperature coefficient of a charge employing the propellant.

We have provided a first proof-of-principle of a novel ballistic concept that holds the promise of significant increases in performance - a muzzle velocity increase of 13% in the 155-mm Howitzer - with minimal impact on propellant production requirements and weapon systems. The real challenge for the remainder of our research effort is to bring the concept to a maturity sufficient for exploition by the charge design community.

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